OPTICAL DIAGNOSTICS FOR THERMAL BARRIER COATINGS, J.I. Eldridge*, C.M. Spuckler, and T.J. Bencic, NASA Glenn Research Center, Cleveland, OH; R.E. Martin, Cleveland State University, Cleveland, OH.

The translucent nature of ceramic oxide thermal barrier coatings (TBCs) provides an opportunity to employ optical probes to monitor temperature gradients and buried damage propagation within the coating. An important advantage of noncontact optical diagnostics is that they are amenable to health monitoring of TBCs in service. In this paper, two optical diagnostic approaches, operating in different wavelength regimes, are discussed. The first approach is the use of mid-infrared reflectance (MIR) to monitor the progression of TBC delamination produced by thermal cycling. This approach takes advantage of the maximum transparency of the TBCs at mid-infrared wavelengths, in particular, between 3 and 5 microns. Recent progress in extending the MIR method to a more practical visual inspection tool will be presented. A second approach, using visible wavelengths, is the embedding of thermographic phosphors within the TBC to add sensing functions to the coating that can provide depth-selective information about temperature gradients and TBC integrity. Emphasis will be given to the use of fluorescence decay time measurements to provide temperature readings from a thermographic phosphor layer residing beneath the TBC.

Optical Diagnostics for Thermal Barrier Coatings

J. I. Eldridge, C.M. Spuckler, and T.J. Bencic
NASA Glenn Research Center
Cleveland, OH

R.E. Martin
Cleveland State University
Cleveland, OH

28th Annual Cocoa Beach Conference
January 29, 2004

Background

- Practical and reliable diagnostic tools are required for TBC health monitoring and to enable confident measurement of TBC performance.
  - Risk of TBC failure restricts application of TBCs
    - Requires extreme safety margins for TBC replacement

      or

    - Limited to temperatures at which unprotected component can survive
  - Accurate measurement of TBC performance is essential to development of ~~of higher performance~~ improved coatings.
- Measurements must be depth-penetrating & nondestructive.
  - Damage propagation is buried below surface.
- TBC translucency allows "window" for optical techniques to provide depth-penetrating, nondestructive diagnostics.

Established Optical Techniques

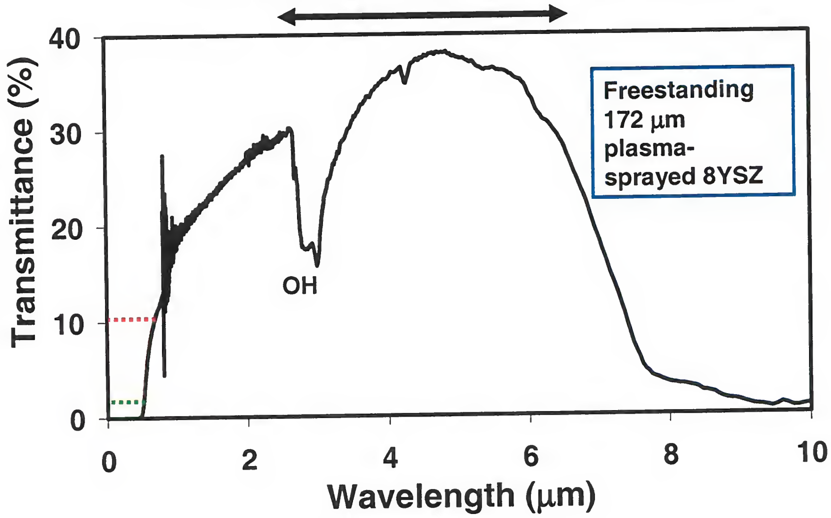
- Infrared (IR) pyrometry provides depth-averaged TBC temperature measurements.
  - Long wavelengths (>10 μm) can provide near surface measurements.
  - Cannot probe thermal gradients.
- Piezospectroscopy (Cr^{3+} luminescence) has been demonstrated to monitor stress state in thermally grown oxide (TGO) beneath TBC. (U. California—Santa Barbara, U. Connecticut)
  - Very difficult to obtain luminescence signal through highly attenuating plasma-sprayed TBCs.
  - Measured TGO stress relaxation occurs immediately preceding or simultaneous with TBC failure; therefore does not provide early warning.
- IR thermography reveals damage-induced "hot spots" & lateral thermal profiles.
  - No depth sensitivity for probing thermal gradients.
  - Significant damage required to produce "hot spots."
  - Measuring transient response to flash not practical for engine testing.

Two Recent Approaches

- Mid-infrared (MIR) reflectance
  - \+ Take advantage of maximum TBC transparency at MIR wavelengths to monitor buried damage progression & erosion.
  - \+ May be sensitive to early stages of TBC failure.
  - \+ Steady-state reflectance images simpler to implement for engine testing than transient-based thermography.
  - – Obscured by surface contamination (misleading results).
  - – Unsuitable for high temperature measurements.
  - – Depth-penetrating, not depth-resolved.
- Luminescence-sensing for TBCs incorporating thermographic phosphors†
  - \+ Strategic placement of luminescent layers will provide depth-resolved information on TBC temperature gradients & integrity.
  - \+ Lower TBC transmittance at visible wavelengths offset by extremely high contrast-producing interaction (luminescence).
  - \+ Amenable to high temperature measurements.
  - – Obscured by surface contamination (loss of signal, no misleading results).
  - – Thermographic phosphor incorporation may degrade TBC performance.

† Demonstrated by S.W. Allison et al., ORNL; J.P. Feist & A.L. Heyes, Imperial College.

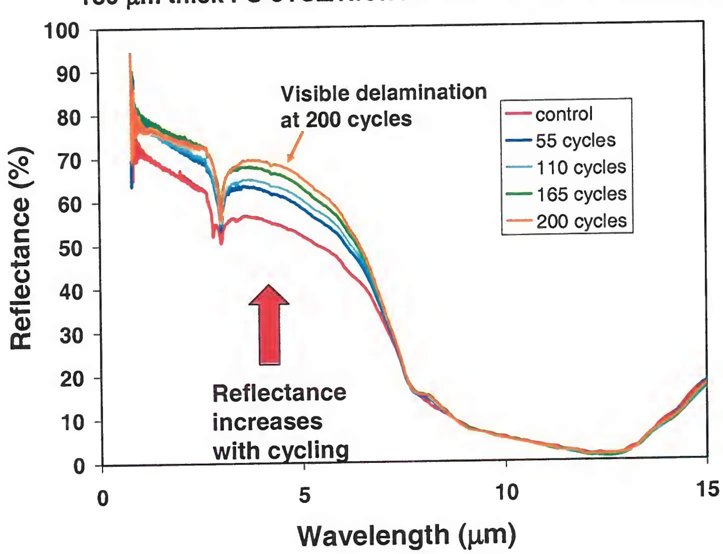
MIR Reflectance Operates at Wavelengths Where TBC Exhibits Maximum Transmittance



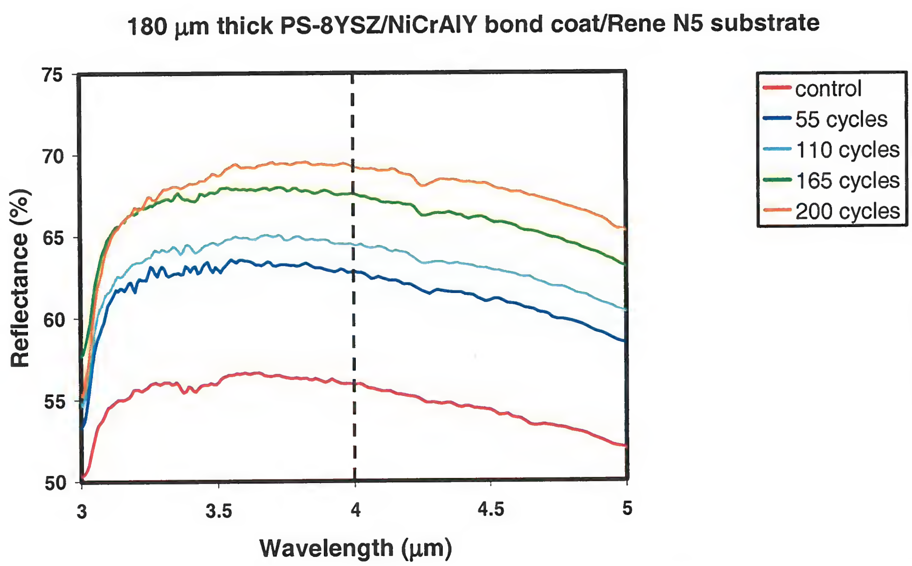
Effect of Furnace Cycling on Hemispherical Reflectance

1 cycle = 45 min @1163°C + 15 min cooling to 120°C in air

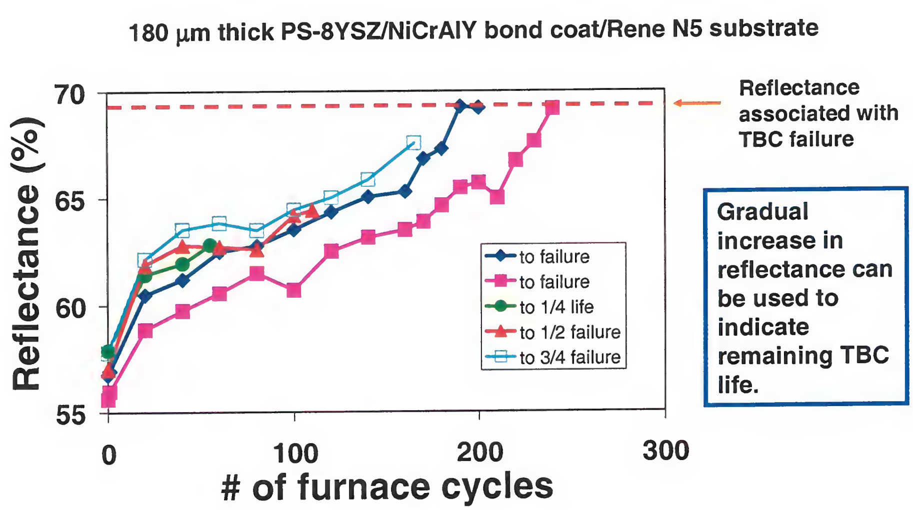
180 μm thick PS-8YSZ/NiCrAlY bond coat/Rene N5 substrate



Effect of Furnace Cycling on Hemispherical Reflectance

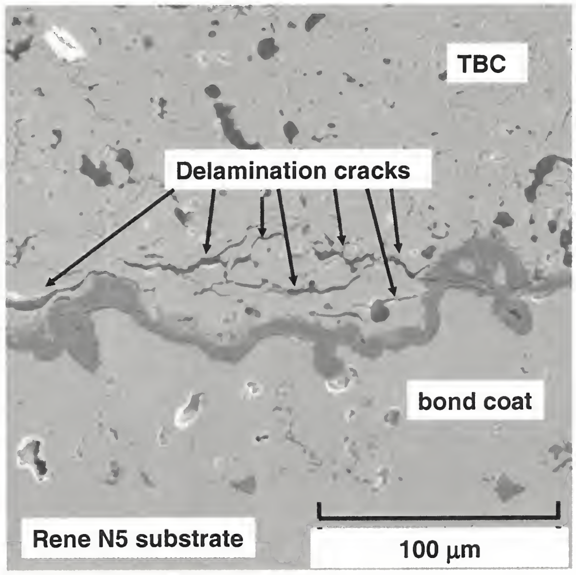


4.0 μm Reflectance as Indicator for Remaining TBC Life

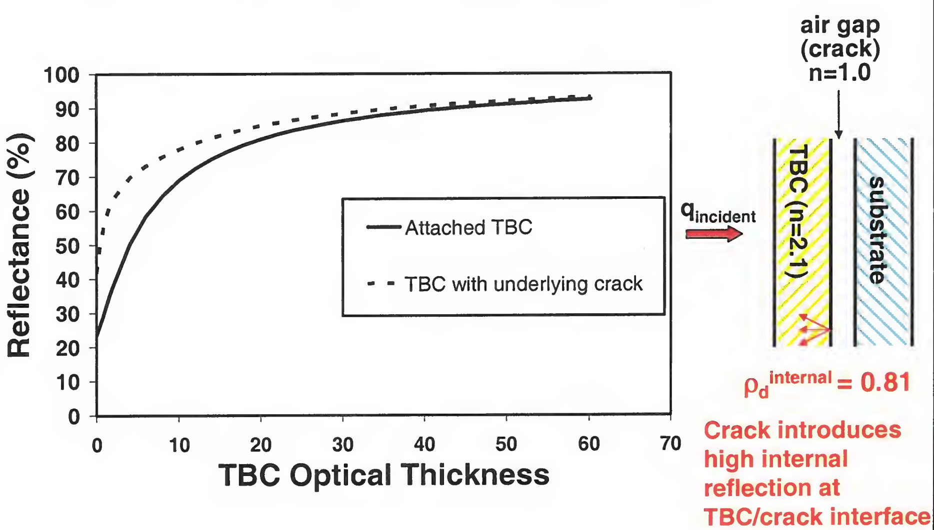


Delamination crack network formed after 150 cycles (3/4 TBC life)

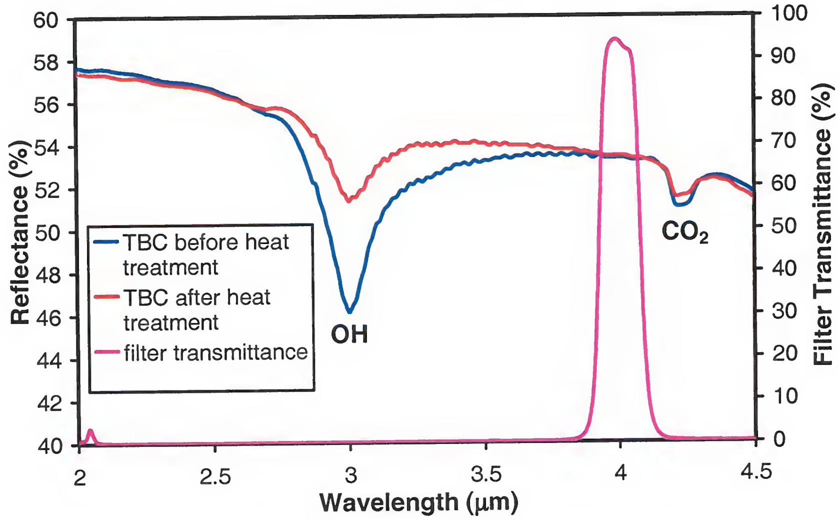
Gradual progression allows effective health monitoring



Predicted Effect of Crack on Hemispherical Reflectance
(based on zero-absorption four-flux model)

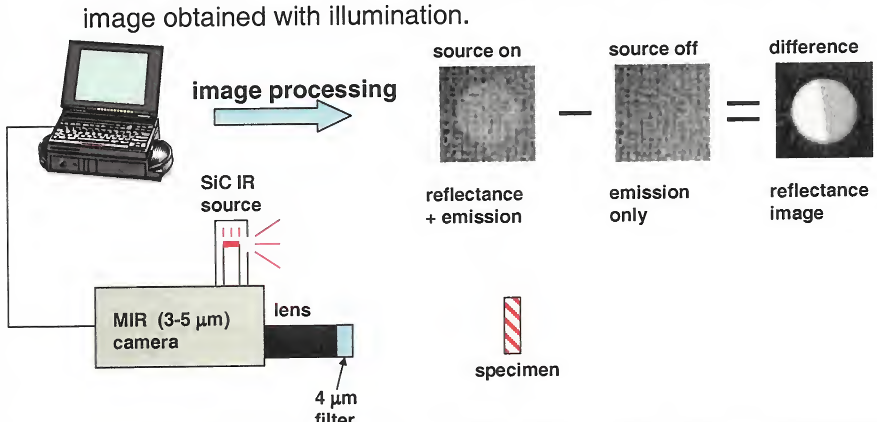


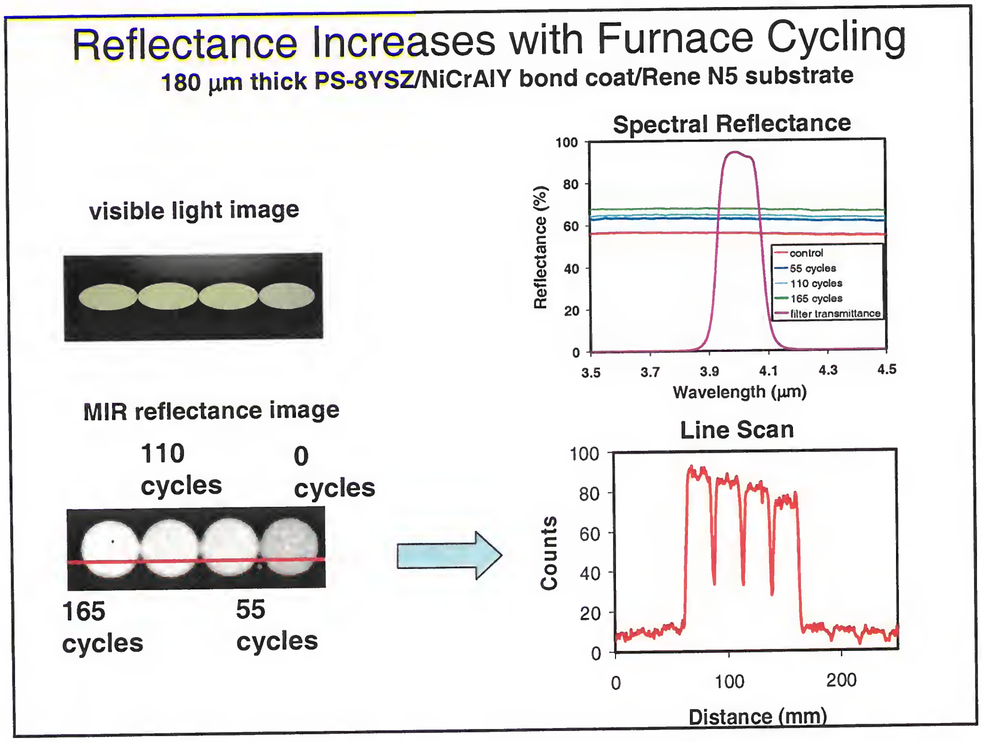
Filtering at 4 μm Avoids OH and CO_2 Interference

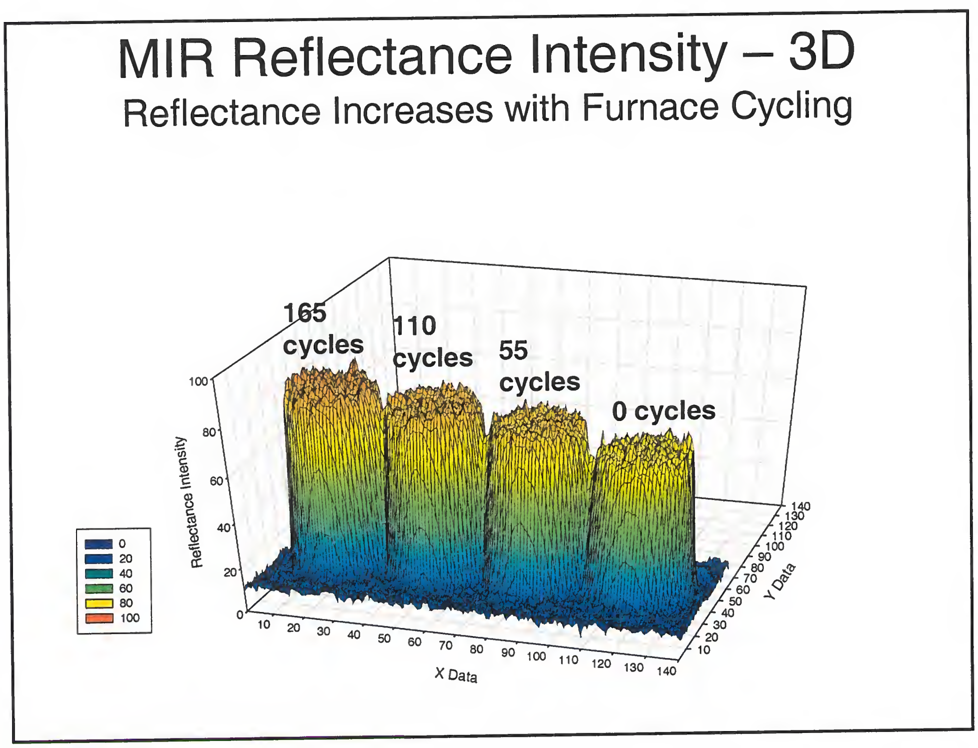


MIR Reflectance Imaging Approach

- Imaging approach is a more practical health monitoring tool using visual inspection that provides the spatial resolution to identify areas of buried damage or erosion.
- Because all objects are MIR emitters, reflectance images are obtained by subtracting image obtained with no illumination from image obtained with illumination.

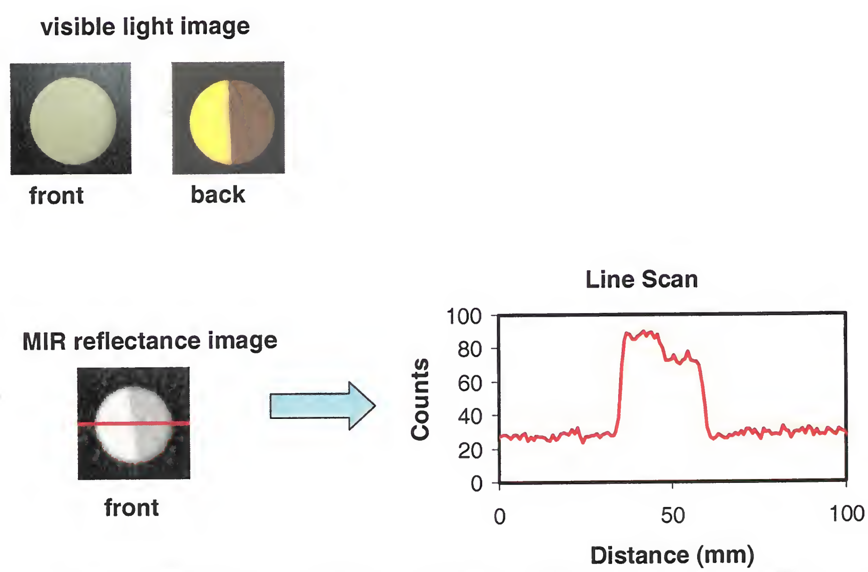



Reflectance Increases with Furnace Cycling
180 μm thick PS-8YSZ/NiCrAlY bond coat/Rene N5 substrate
visible light image
MIR reflectance image
110 cycles
0 cycles
165 cycles
55 cycles
Spectral Reflectance
Reflectance (%)
Wavelength (μm)
control
55 cycles
110 cycles
165 cycles
filter transmittance
Line Scan
Counts
Distance (mm)


MIR Reflectance Intensity – 3D
Reflectance Increases with Furnace Cycling
165 cycles
110 cycles
55 cycles
0 cycles
Reflectance Intensity
X Data
Y Data

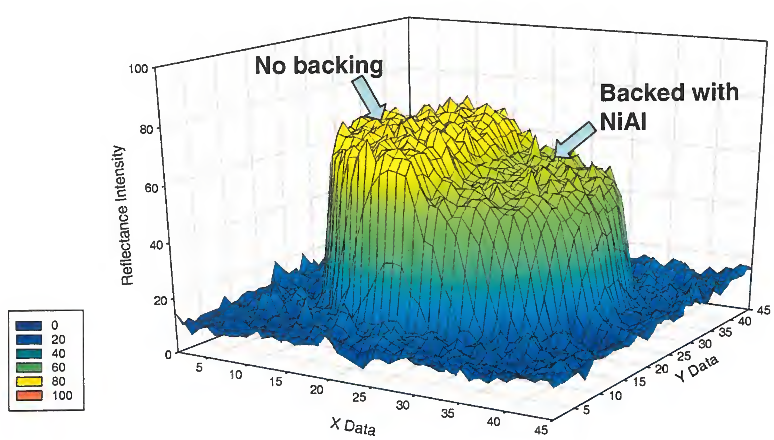
MIR Reflectance Imaging

Effect of NiAl Backing – Simulates Substrate Presence



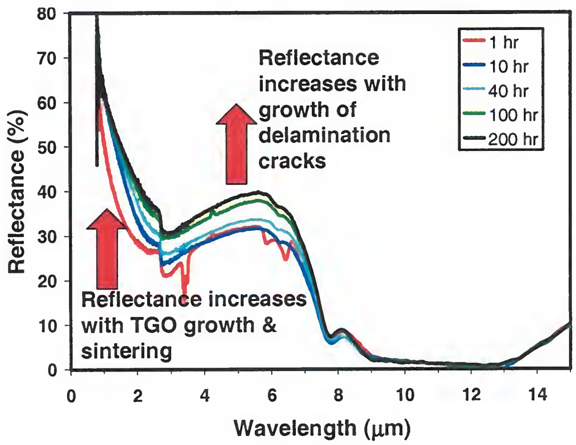
MIR Reflectance Imaging

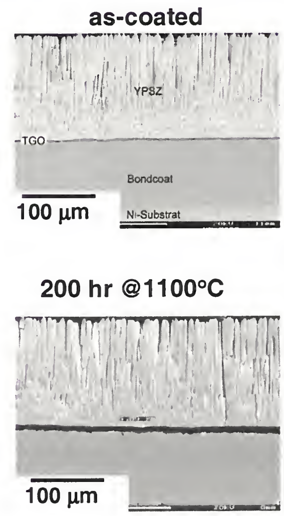
Half-Backed PS-8YSZ TBC



Effect of 1100°C Heat Treatment on Hemispherical Reflectance of EB-PVD TBC

TBC specimens & SEM courtesy of Uwe Shulz, DLR

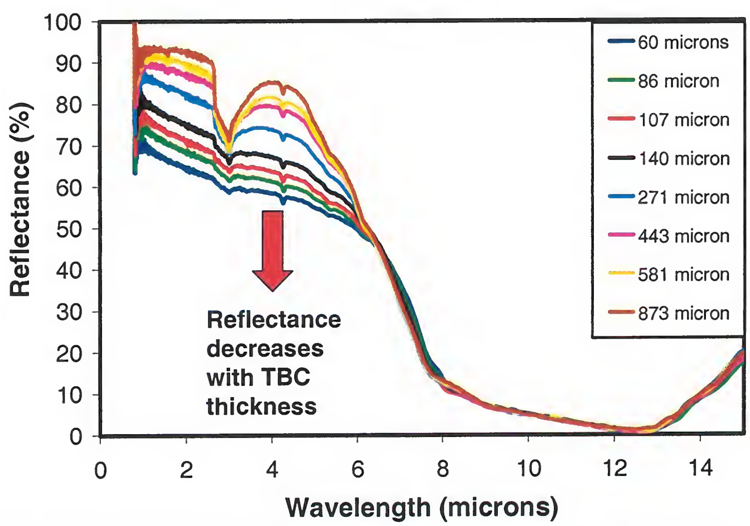




Effect of TBC Thickness on Hemispherical Reflectance

Thickness dependence can be used to monitor erosion

Freestanding plasma-sprayed 8YSZ



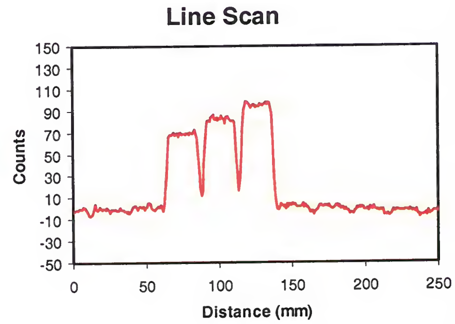
MIR Reflectance Imaging

Thickness Dependence -- Freestanding PS-8YSZ TBCs

visible light image

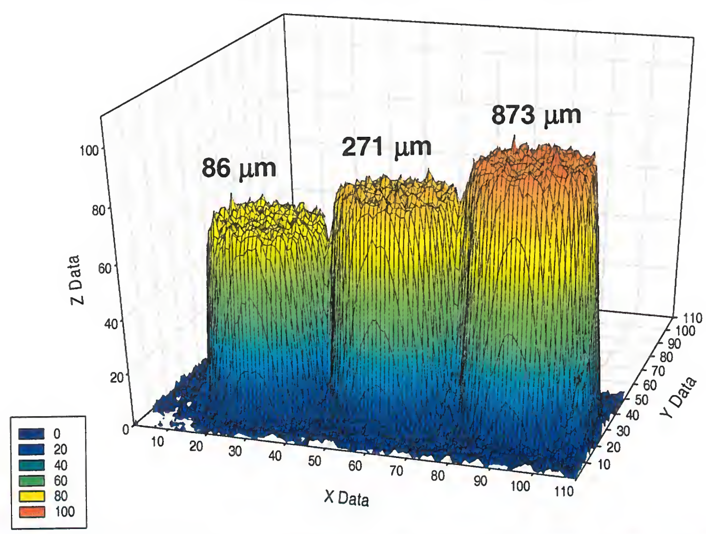
MIR reflectance image

86 μm 271 μm 873 μm



MIR Reflectance Intensity – 3D

Thickness Dependence -- Freestanding PS-8YSZ TBCs
Wide Thickness Range



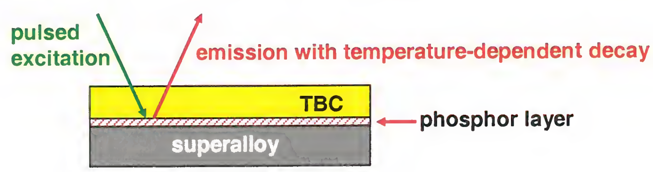
Competing Influences on Hemispherical Reflectance

- **Progression of delamination crack network** increases reflectance (preferentially in 3-5 μm range)
- **Erosion** decreases reflectance (over wider 0.8 to 5 μm range)
- **Sintering** decreases reflectance for plasma-sprayed coatings (preferentially in 0.8 to 3 μm range)
  - Grain coarsening may increase reflectance in EB-PVD coatings
- Effects of **TGO growth** require further study.

Separation of competing effects may be possible from distinguishing spectral signatures, requiring multi-wavelength detection.

Luminescence Sensing Approach

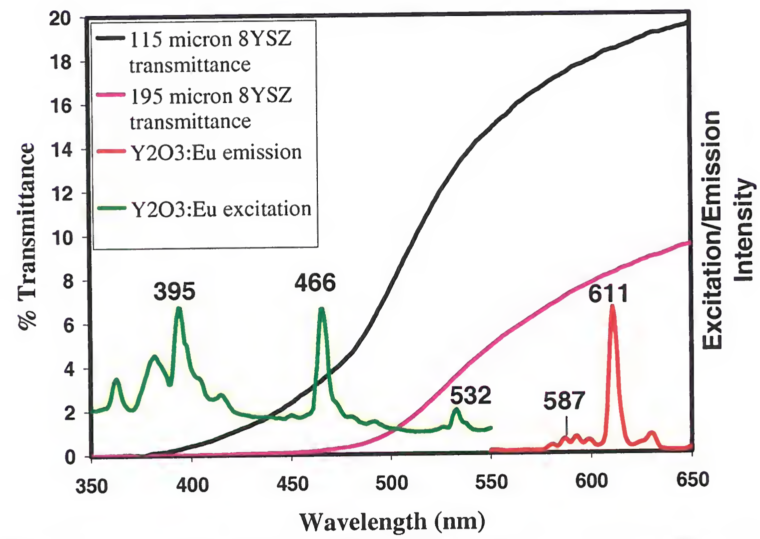
- Explore potential of achieving depth-probing TBC temperature measurements by placing thermographic phosphor layer at desired depth within translucent TBC.



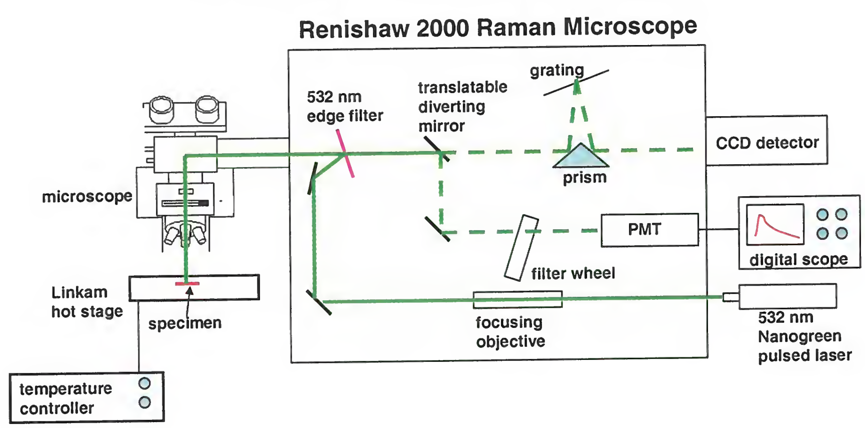
Strategy

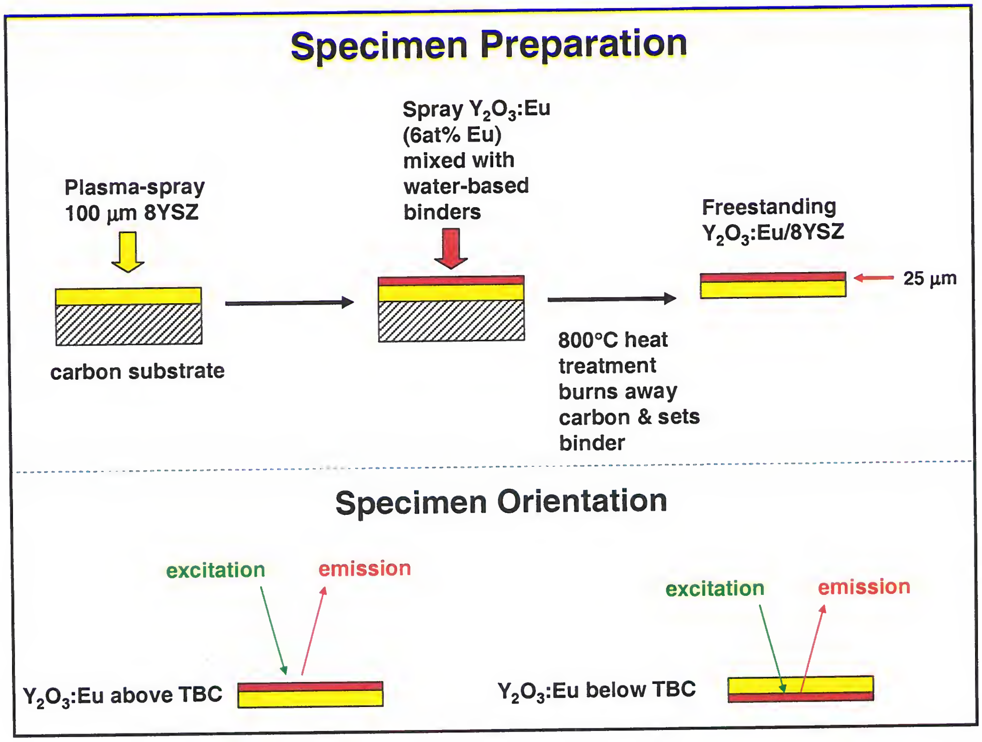
- Select thermographic phosphor that can be excited and emits at wavelengths that can be transmitted through TBC.
  - Severe restriction because most phosphors are best excited by UV wavelengths that do not penetrate TBC.
- Eventually move from distinct phosphor layer to using TBC itself as host for layered doping of luminescent ions. (Feist & Heyes demonstrated doped YSZ can be effective thermographic phosphor.)

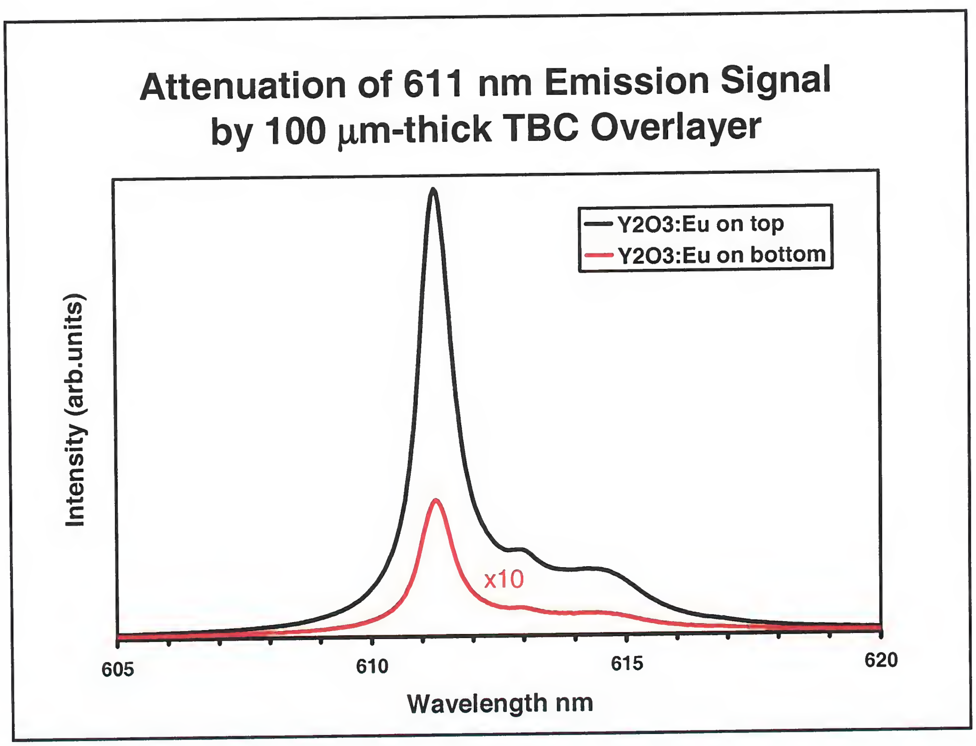
Overlap of Y_2O_3:Eu Excitation and Emission Spectra and TBC Transmittance



Raman-Spectrometer-Based Luminescence Spectra & Decay Time Measurements

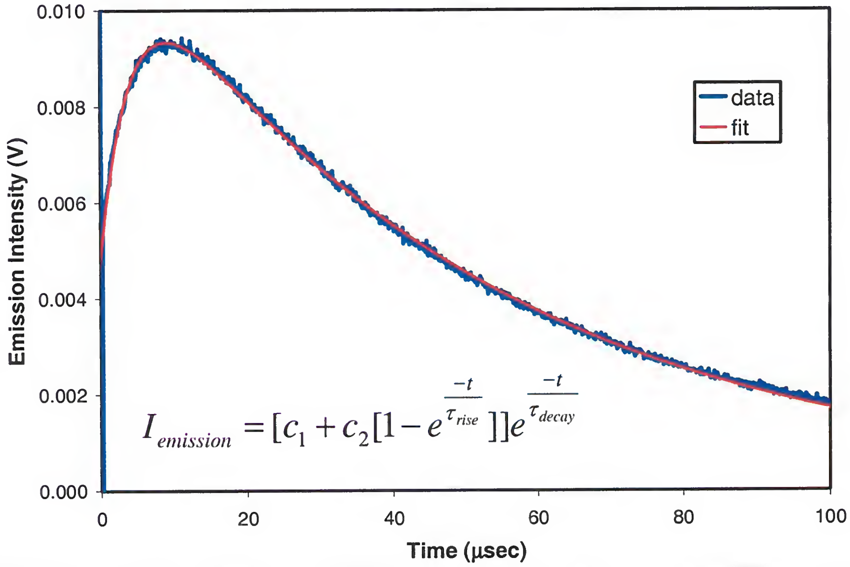



Specimen Preparation
Spray Y_2O_3:Eu (6at% Eu) mixed with water-based binders
Plasma-spray 100 μm 8YSZ
Freestanding Y_2O_3:Eu/8YSZ
25 μm
carbon substrate
800°C heat treatment burns away carbon & sets binder
Specimen Orientation
excitation
emission
Y_2O_3:Eu above TBC
excitation
emission
Y_2O_3:Eu below TBC


Attenuation of 611 nm Emission Signal by 100 μm-thick TBC Overlayer
Y2O3:Eu on top
Y2O3:Eu on bottom
Intensity (arb.units)
x10
605
610
615
620
Wavelength nm

Fitting Fluorescence Decay Curves

611 nm emission from Y_2O_3:Eu beneath TBC at 700°C



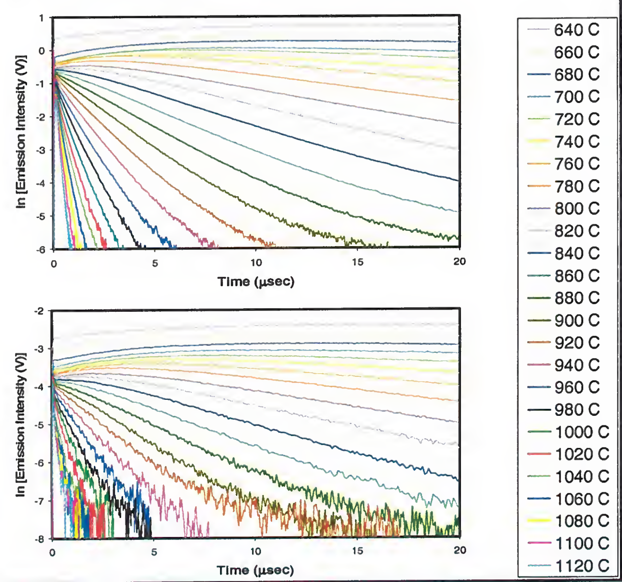
Temperature Dependence of Decay Curves

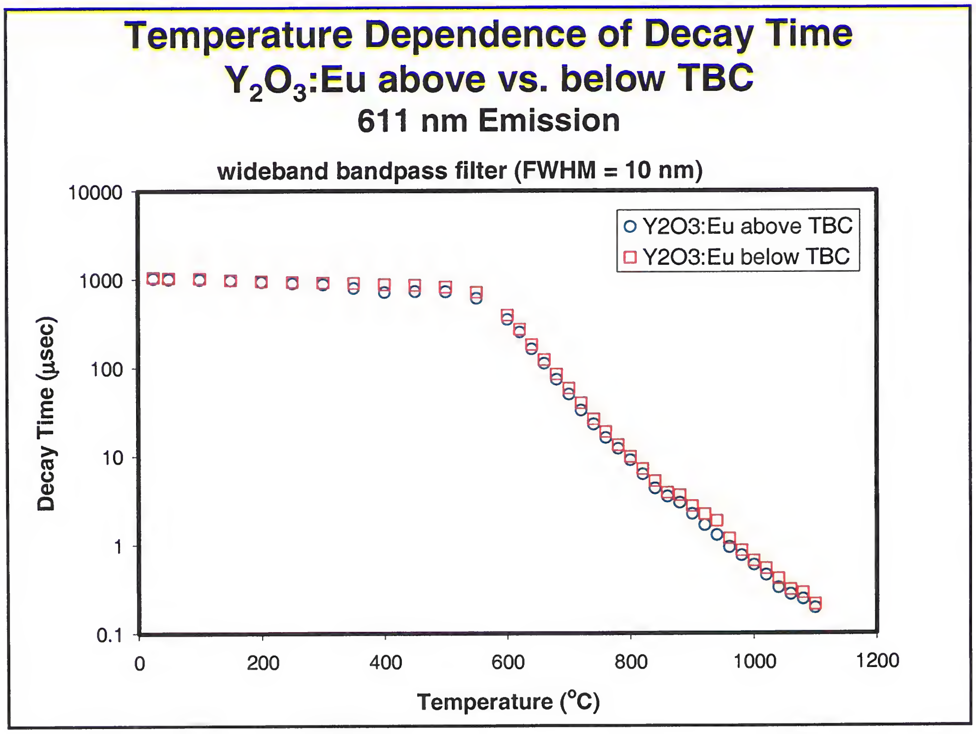
Y_2O_3:Eu above vs. below TBC

611 nm Emission

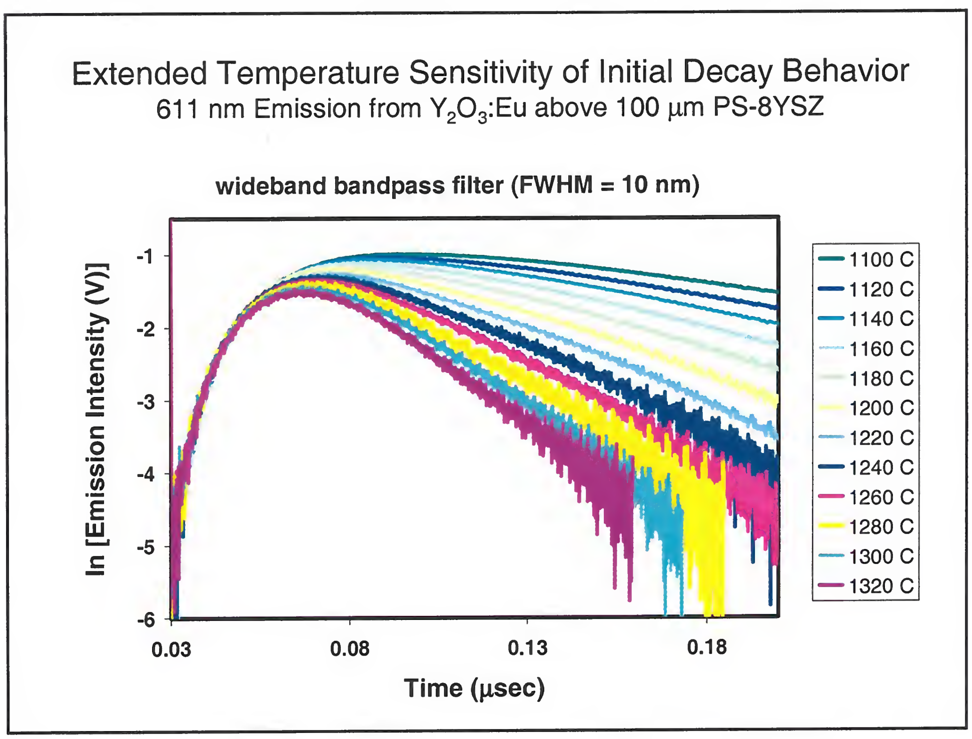
Y_2O_3:Eu above TBC

Y_2O_3:Eu below TBC





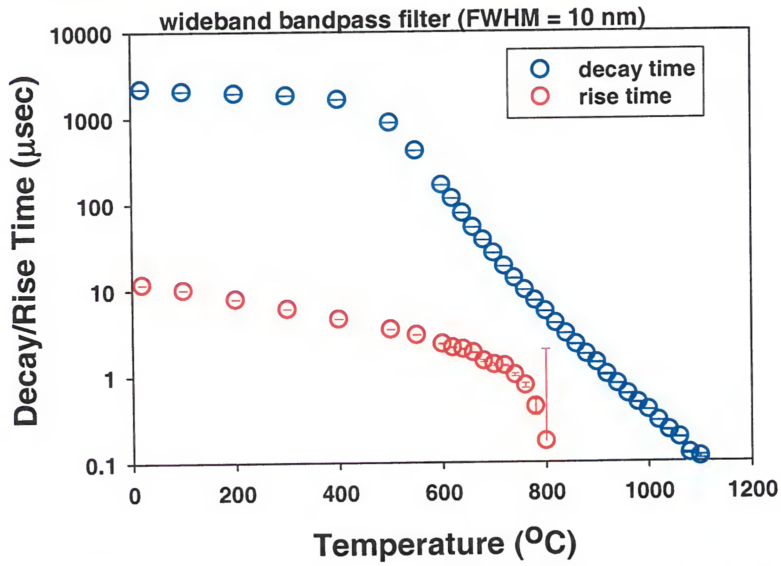
Temperature Dependence of Decay Time
Y_2O_3:Eu above vs. below TBC
611 nm Emission
wideband bandpass filter (FWHM = 10 nm)
Y2O3:Eu above TBC
Y2O3:Eu below TBC
Decay Time (µsec)
10000
1000
100
10
1
0.1
0
200
400
600
800
1000
1200
Temperature (°C)



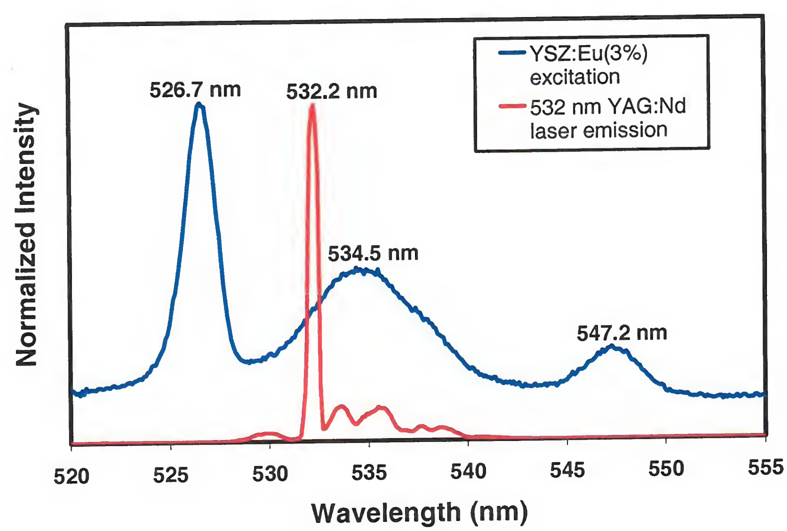
Extended Temperature Sensitivity of Initial Decay Behavior
611 nm Emission from Y_2O_3:Eu above 100 µm PS-8YSZ
wideband bandpass filter (FWHM = 10 nm)
ln [Emission Intensity (V)]
-1
-2
-3
-4
-5
-6
0.03
0.08
0.13
0.18
Time (µsec)
1100 C
1120 C
1140 C
1160 C
1180 C
1200 C
1220 C
1240 C
1260 C
1280 C
1300 C
1320 C

YSZ:Eu Is Effective Thermographic Phosphor

606 nm Emission from YSZ:Eu(3%) Powder

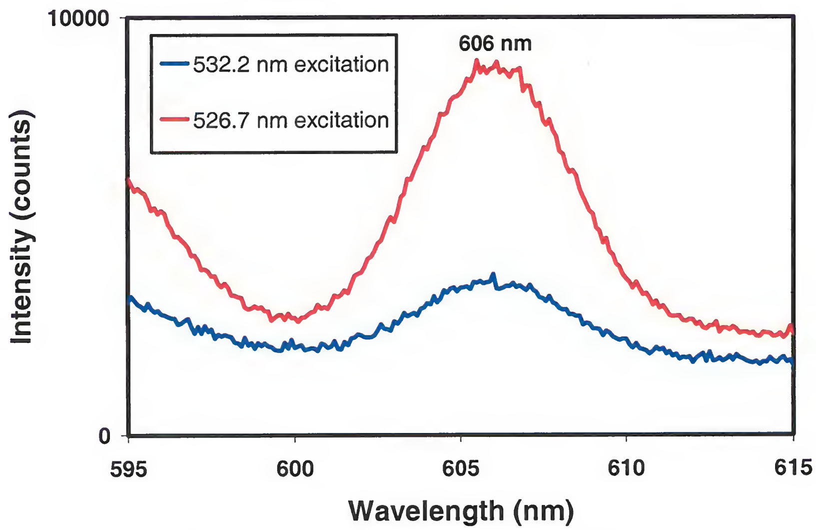


High-Resolution Comparison of YSZ:Eu(3%) Excitation and YAG:Nd (Doubled) Laser Emission



Emission Maximized by Optimizing Excitation Wavelength

606 nm Emission from YSZ:Eu(3%) Powder



Summary

- MIR Reflectance
  - Furnace cycling measurements show good correlation between reflectance & remaining TBC life.
    - Sensitive to early stages of TBC failure.
  - Reflectance at 4 μm shows good sensitivity to buried cracks and desirable insensitivity to OH or CO_2 or effects of sintering.
  - Reflectance thickness dependence can be used to monitor erosion.
  - Potential for separating competing influences on reflectance by multi-wavelength detection.
  - MIR reflectance imaging provides visual inspection capability.
    - Provides spatial resolution to identify areas of partial delamination or erosion.

Summary

- Luminescence-sensing for TBCs using thermographic phosphors
  - Successful decay-time-based temperature measurements up to 1100°C from Y_2O_3:Eu layer below 100-μm-thick TBC.
    - Sufficient transmission of 532 nm excitation and 611 nm emission for depth-penetrating measurements
  - Evidence for temperature measurement capability to 1300°C using initial decay.
  - Rise time provides better temperature indication below 600°C.
  - Successful decay-time-based temperature measurements up to 1100°C (with potential to 1300°C) for YSZ:Eu powder.
    - Promising for achieving luminescence sensing by low level layer doping during TBC deposition.
  - Emission signal can be optimized by "tuning" excitation wavelength.

Conclusions

- Optical diagnostics can be successfully applied to translucent TBCs.
- MIR reflectance can be used as a health monitoring tool to evaluate TBC erosion and delamination crack progression.
- Strategically selected and located thermographic phosphors show promise for adding depth-selective temperature-sensing functions to TBCs.

Acknowledgments

- Chuck Barrett – furnace cycling
- George Leissler & Sandy Leissler – spraying TBC specimens
- Luke Hertert – Labview programming
- Judy Auping – software to simplify decay time analysis
- Uwe Shulz (DLR) – EB-PVD coatings
- Steve Allison & Dave Beshears (ORNL) – phosphor coating